March 1, 1999

Dr. N. Anne Davies
Associate Director for Fusion Energy Sciences
Office Of Science
ER-50, Germantown
U.S. Department of Energy
Germantown, MD 20874-1290

Dear Anne:

This letter responds to your request to develop "recommendations to the Department on how we could best maximize the effectiveness of our international collaborations over the next three to five years". I am very pleased to address this challenge, since the US fusion program goals are best approached by an integrated program that recognizes and exploits the opportunities afforded by the domestic program and by international collaboration.

Consistent with your direction that "recommendations should be developed with input from and supported by the fusion community at large", I commissioned a multi-institutional process to characterize the on-going international collaborations and to suggest general and specific directions for future collaborations. To characterize the present program, the working group contacted institutional and programmatic leaders and compiled a list of hundreds of on-going international collaboration tasks and analyzed the distributions of these tasks. To provide the basis for suggestions of future activities, the working group worked in a top-down fashion, proceeding along both concept-lines and topic-lines, identifying leading opportunities for research based on the characteristics of foreign facilities and the directions of the foreign programs. My recommendations to you have been developed by consideration of the material produced by the working group.

As a policy, the US and other nations should sustain or form appropriate new international partnerships and collaborations to draw on complementary capabilities and to utilize facilities worldwide to address the fusion program's critical issues in a coordinated and mutually beneficial manner.

At present, the US fusion program engages in significant international collaboration in both experimental and theoretical activities, under a variety of international agreements. The program's international collaborations span a wide range of scales --- from individual investigators visiting foreign facilities to multi-institutional teams designing, fabricating, and utilizing hardware for the conduct of pioneering research on the leading facilities worldwide. The survey conducted in response to your request indicates that experimental collaborations entail about $25M/year in US effort, divided by concept as indicated in the following table.

Experimental Area	Level of US Experimental Effort	Percentage of the Total Experimental International Collaborations Budget
Tokamaks	$8.M	33%
Alternate MFE Concepts	$2.M	8%
Inertial Fusion Energy	$0.4M	2%
Technology	$14.M	57%
TOTAL	$24.4M	100%

In the tokamak program, the main emphases are in areas that are complementary to the domestic program such as joint programs to explore the scaling of plasma effects with size and studies of phenomena that are inaccessible on domestic programs due to the domestic unavailability of facility capabilities such as deuterium-tritium operation for burning plasma studies and sets of plasma control tools. In the alternate concepts area, the largest activity involves participation in experiments on large international stellarators. In the inertial confinement fusion program, work focuses on heavy ion driver development. In the technology program, the largest segments are in studies of the effects of irradiation on structural materials, in the development and operation of tritium systems, in the fabrication and testing of power and particle control systems, in the completion of fabrication and testing of a large superconducting magnet, and in the development of heating, current drive and fueling systems.

Future international collaborations should be developed as an integral part of the overall US fusion program planning process --- not independently. The activities should be guided by identification of the most promising opportunities for achieving US program goals by utilization of domestic and international facilities and by participation in foreign programs. The formality of the planning process must be graded, with minimal oversight of the choices by individual investigators to pursue their research through international collaborations and with formal joint planning for the large-scale activities. A source of flexible funding for travel would greatly facilitate collaborations by smaller groups.

Regarding future US participation in large-scale international programs that either exist or are under construction, the following directions and opportunities are recommended.

- In the tokamak program, burning plasma physics should be studied on the JET facility due to its unique DT capability. Advanced tokamak physics should be pursued on JT-60U in Japan and on JET and medium scale devices in Europe, coupled with the US domestic facilities C-MOD and DIII-D. Long-pulse advanced tokamak physics should be studied on the superconducting KSTAR under construction in Korea. Size-scaling should be studied on JET and JT-60U, jointly with the US facilities.

- In the alternate concepts program, the prime focus for stellarator collaboration should be the Large Helical Device (LHD) in Japan, with participation on the more modest devices W7-AS and TJ-II; the US should plan participation in the European W7-X, which is under construction in Europe. The US's spherical torus programs (NSTX, Pegasus, HIT-II and CDX-U) should coordinate with the world ST community (MAST in U.K., Globus-M in Russia, TS-4 in Japan, and ETE in Brazil), emphasizing their complementarity. The US Reversed Field Pinch program should remain coupled to the world program, and should encourage foreign participation on the MST device in Wisconsin.

- In the inertial fusion energy program, bilateral and multinational international activities should be encouraged; inclusion of IFE in IEA fusion agreements should be considered. Target physics collaboration on the study of fast igniter physics with the Japanese Gekko laser program, the U.K.'s Rutherford Laboratory, and the GSI in Germany would be most timely, especially in light of the closure of the US Nova in 1999, to contribute to the basis for fast ignition experiments on the US NIF, under construction at LLNL. Heavy ion driver work with GSI in Germany, ITEP in Russia, and Japan are promising opportunities. Laser driver development with France, Britain and Japan are strong possibilities.

- MFE theory and modeling research collaborations should be sustained in the areas of turbulence and transport, MHD and energetic particle stability, edge and divertor modeling, radio frequency heating and current drive, and basic theory and computational initiatives. These programs should also address the development and application of physics design tools for use by the designers of next step facilities.

- In the technology program's materials program, irradiation of structural materials should be continued at international facilities. Heating and current drive collaborations on JET could develop and test an improved matching and/or ELM protection circuitry and improve power-handling capability; such collaborations would be mutually beneficial and would advance both the US technology program and its science program on confinement, optimization and burning plasma physics; development and participation in the operation of a long-pulse ion cyclotron (IC) launcher and a lower hybrid (LH) launcher for KSTAR are opportunities for synergy between the technology and science programs; participation in the KSTAR diagnostics program would involve the US in the program in plasma control and long-pulse operation. In power and particle handling technology, on-going US programs on JET (erosion-redeposition, and tritium retention and removal), and on LHD, and international participation on US domestic facilities (PISCES, Plasma Materials Test Facility/Sandia, and Tritium Plasma Experiment/Sandia/Los Alamos) are planned to continue. On blankets, issues of MHD for liquid metal flow, thermomechanical performance and material interaction of solid breeders, and neutronics are candidates for continued or increased collaborations. In the magnetics area, data from testing of the ITER CS Model Coil will provide significant benefit to the US; collaborations on KSTAR (helium isolator, fiber optic quench sensors, and field joint tests) and MAST (felt metal joints) are proposed. In operations processes (tritium, safety and remote handling), tasks in fusion-fuel processing, analysis of JET dust, improvement of JET's impurity processing and cryogenic distillation systems, and non-intrusive diagnostics of PFC motion are proposed.

Regarding international tokamak facilities that are not yet under construction, the US should pursue opportunities for participation in an international burning plasma facility, including research on ITER if the international parties proceed to construction and on Ignitor if the Italians and/or Europeans choose to advance that project to construction. The US should seek to understand the plans and technical basis for HT-7U in China for studies of long-pulse advanced tokamak physics.

In planning future international collaborations on major facilities, such as a burning plasma experiment, we should be mindful of a relevant recommendation from the much-praised document <u>The Decade of Discovery in Astronomy and Astrophysics</u> (pp. 119-120), the report of the NRC study aimed at setting priorities in astronomy and astrophysics, chaired by Professor John Bahcall: "The Committee recommends that international cooperation be considered for the development of a major initiative if such a project draws on complementary capabilities of different nations or requires resources beyond those that can be provided by the United States alone." We should also note that the Bahcall report states that "Sometimes, international collaboration and scientific goals are most effectively advanced when nations build their own unique facilities, providing access to qualified scientists from other nations".

Attached is the working group's report that includes an overview of the on-going international collaboration activity and identifies general opportunities for international activities that would significantly advance progress on achieving the US fusion program goals.

Sincerely,

Robert J. Goldston
Director

Enhancing the Effectiveness of International Collaborations in the U.S. Fusion Energy Sciences Program

March 1, 1999

1. Process

Responding to Dr. Anne Davies' request to develop "recommendations to the Department on how we could best maximize the effectiveness of our international collaborations over the next three to five years" and that "recommendations should be developed with input from and supported by the fusion community at large", PPPL Director Robert J. Goldston asked Dr. Ned Sauthoff (PPPL) to involve the community in gathering inputs. An organizing committee, consisting of Dr. W. Nevins (LLNL), Dr. M. Saltmarsh (ORNL), Dr. N. Sauthoff (PPPL), and Dr. K. Young (PPPL), was established and planned a process that would develop recommendations in a top-down fashion. Topical coordinators were recruited in the areas of tokamaks (Dr. T. Simonen and Dr. K. Young), innovative concepts (Dr. M. Peng and Dr. J. Lyon), Inertial Fusion Energy (Dr. W. Hogan), theory (Dr. V. Chan and Dr. J. Van Dam) and technology (Dr. M. Saltmarsh), to use recent U.S. fusion program documents to identify high priority topical issues that should be the basis for the international collaborations program. Foreign facility coordinators were recruited from the US community and charged with identifying the research directions, facility capabilities, and facility management's recommended areas for U.S. participation. The resultant issues and tasks (both on-going and proposed) were compiled into a database which served as a the focus for a two-day meeting at Princeton, during which the issues and the opportunities for addressing high priority US fusion program goals were discussed. Following the meeting, the topical coordinators worked with group members to refine and analyze the lists of tasks, to draft text describing programmatic directions for international collaborations in the topical areas and the roles of specific foreign facilities in each topical area, and to identify especially compelling opportunities for significant increased near-term investment.

Participants and contributors in the planning included R. Aamodt (LodeStar), Charles Baker (ITER US Home Team/UCSD/VLT), Dan Baker (GA), D. Barnes (LANL), Roger Bengtson (UFA; UT), S. Berk (DOE/OFES), Everett Bloom (ORNL), V. Chan (GA), Kenneth Gentle (UT), Bill Herrmannsfeldt (SLAC), Bill Hogan (LLNL), J. Hosea (PPPL), Bruce Lipschultz (MIT), Jim Lyon (ORNL), Earl Marmar (MIT), Warren Marton (DOE/OFES), S. Milora (ORNL), P. Mioduszewski (ORNL), D. Monticello (PPPL), F. Najmabadi (UCSD), H. Neilson (PPPL), Bill Nevins (LLNL), Richard Nygren (SANDIA), Erol Oktay (DOE/OFES), Al Opdenaker (DOE/OFES), H. Park (PPPL), M. Peng (ORNL), Stewart C. Prager (U. Wis), David Rasmussen (ORNL), Michael Saltmarsh (ORNL), Ned Sauthoff (PPPL), John Schmidt (PPPL), T. Simonen (GA), Dale Smith (ANL), David Swain (ORNL), E. Synakowski (PPPL), Tony S. Taylor (GA), James W. VanDam (UT), Ken L. Wilson (SANDIA), Steve Wolfe (MIT), G. Wurden (LANL), M. Yamada (PPPL), Kenneth Young (PPPL), Mahmoud Youssef (UCLA)

The charge follows from the "DOE Strategic Plan for Fusion International Collaborations", which itself was based on a community plan entitled "Technical Opportunities for International Collaborations by the U.S. Fusion Program". The DOE strategic plan specified three major thrust areas:

(1) In the area of burning plasma and tokamak performance:

- participate in the three-year extension of the ITER Engineering Design Activities, restructuring that participation to emphasize development of lower cost design options to enhance the likelihood of constructing and operating a burning plasma physics facility, exploration of how these options may impact fusion development paths, and a refocusing of the U.S. Fusion technology program on meeting the needs of the restructured U.S. fusion energy sciences program.
- seek to discuss with the proper authorities on the European Union side the possibility that the U.S. could become a major collaborator on JET, the only existing fusion facility (currently authorized through 1999) with advanced performance capabilities that can operate with prototypic fusion power plant fuels, Deuterium and Tritium.
- pursue development of an active collaboration on the physics of energy confinement and transport barrier formation on JT-60U, a flexible Japanese tokamak facility with equivalent break-even performance capability.
- promote international topical collaborations in the areas of size scaling, power and particle control and long pulse operation.

(2) In the area of innovative concept developments:

- establish a program of international collaborations on spherical tori, including inviting international participation on the National Spherical Torus Experiment in the U.S.
- pursue opportunities for collaboration on stellarators through participation in the Large Helical Device program in Japan and the Wendelstein program in Germany.
- expand bilateral collaborations in Inertial Fusion Energy (IFE), and explore the incorporation of IFE issues into the fusion energy activities conducted under the auspices of the International Energy Agency.

(3) In the area of fusion technology:

- begin discussions of future fusion development paths with our international colleagues.
- seek to deploy U.S. technologies on fusion experiments worldwide to access test conditions unavailable domestically, particularly on scientific issues related to long pulse/steady state operation, high power densities, and reliability.
- pursue the conduct of joint development work on the key feasibility issues for fusion technologies and materials, such as neutron irradiation effects, using unique fusion facilities worldwide.

As specified in the charge letter, the Group considered "how the available resources could be used to continue or enhance existing collaborative activities, begin new activities on existing fusion devices abroad such as JET, LHD, and JT-60U, or begin activities on as yet to be constructed facilities such a KSTAR or Wendelstein 7-X." The Group spent considerable discussing the charge "how best to coordinate science and technology activities to obtain the maximum possible leverage from both aspects of fusion research", considering both the missions of the Science and the International and Technology Divisions within OFES and the synergies that could enhance the effectiveness of the overall OFES program.

As suggested in the charge letter, the Group's draft recommendations were "discussed with the Executive Committee for the relevant agreement" during the period of the IAEA meeting (October 1998) "to assure that other parties to the agreements have the same interests and sense of priorities".

The remainder of this attachment provides:

(a) an overview of the on-going international collaboration activity; and

(b) general opportunities for international activities that would significantly advance progress on achieving the US fusion program goals.

2. Overview of On-going (FY99) International Collaboration Activity

To provide context for the development of recommendations, the group consulted institutions and performers to estimate the level of international collaboration activity being performed in FY99 and to analyze the topical distributions of the activity. The estimates were based on a list of several hundred tasks, which were sorted into the topical areas of tokamaks, innovative MFE concepts, inertial fusion energy, and technology. Only the US DOE/OFES funds were counted in the tabulation. The theory program participants could not segregate their international activities since the linkages are so extensive that it is difficult to distinguish domestic from international activity; consequently, theory program collaborations are not included in this compilation and analysis.

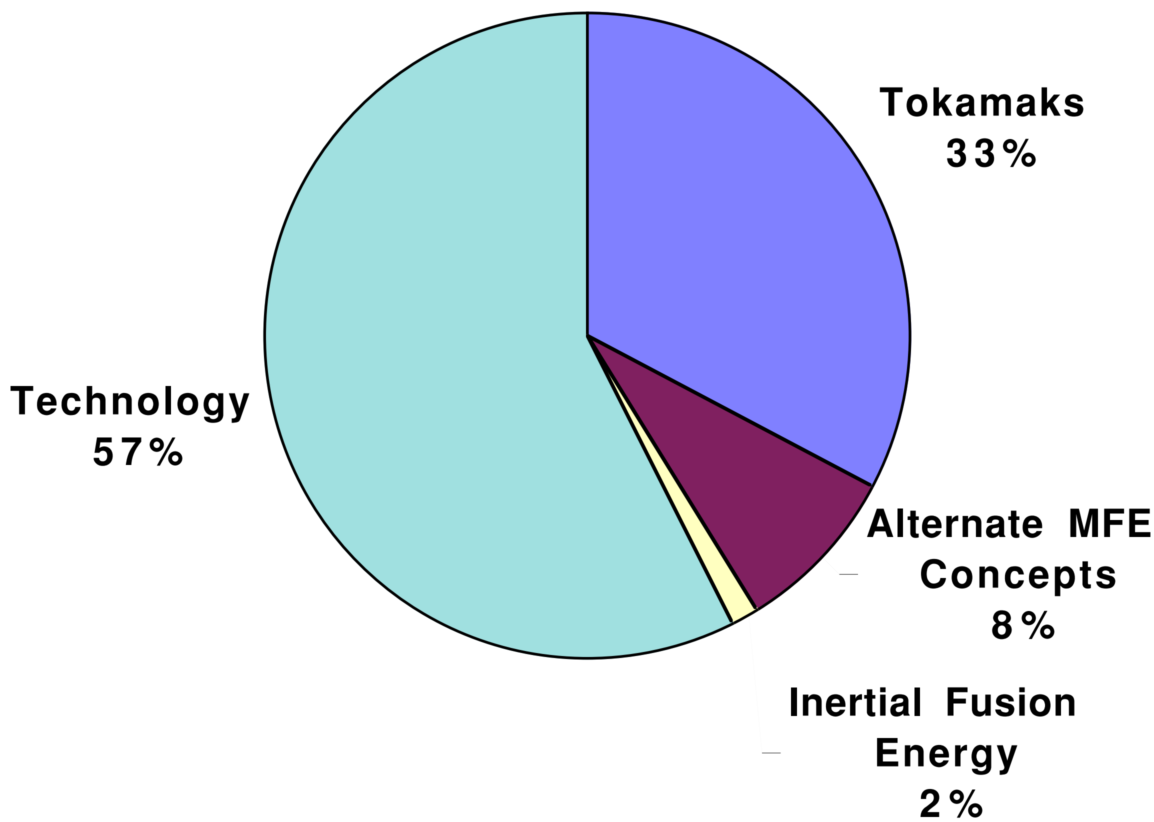

Figure 1. Distribution of the $25M of FY99 international collaborations activity in the US fusion program overall

At the highest level, the FY99 international collaboration activity (as measured by US budget expenditure) totaled roughly $25M. This activity was divided among the major topical areas as shown in the pie chart of Figure 1. The technology program is the largest component (at roughly $14M), followed by the tokamak program (at roughly $8M), the alternate concepts program (at roughly $2M), and the inertial fusion energy program (at roughly $0.4M). The scopes and topical distributions in each of these areas will be described in the following paragraphs.

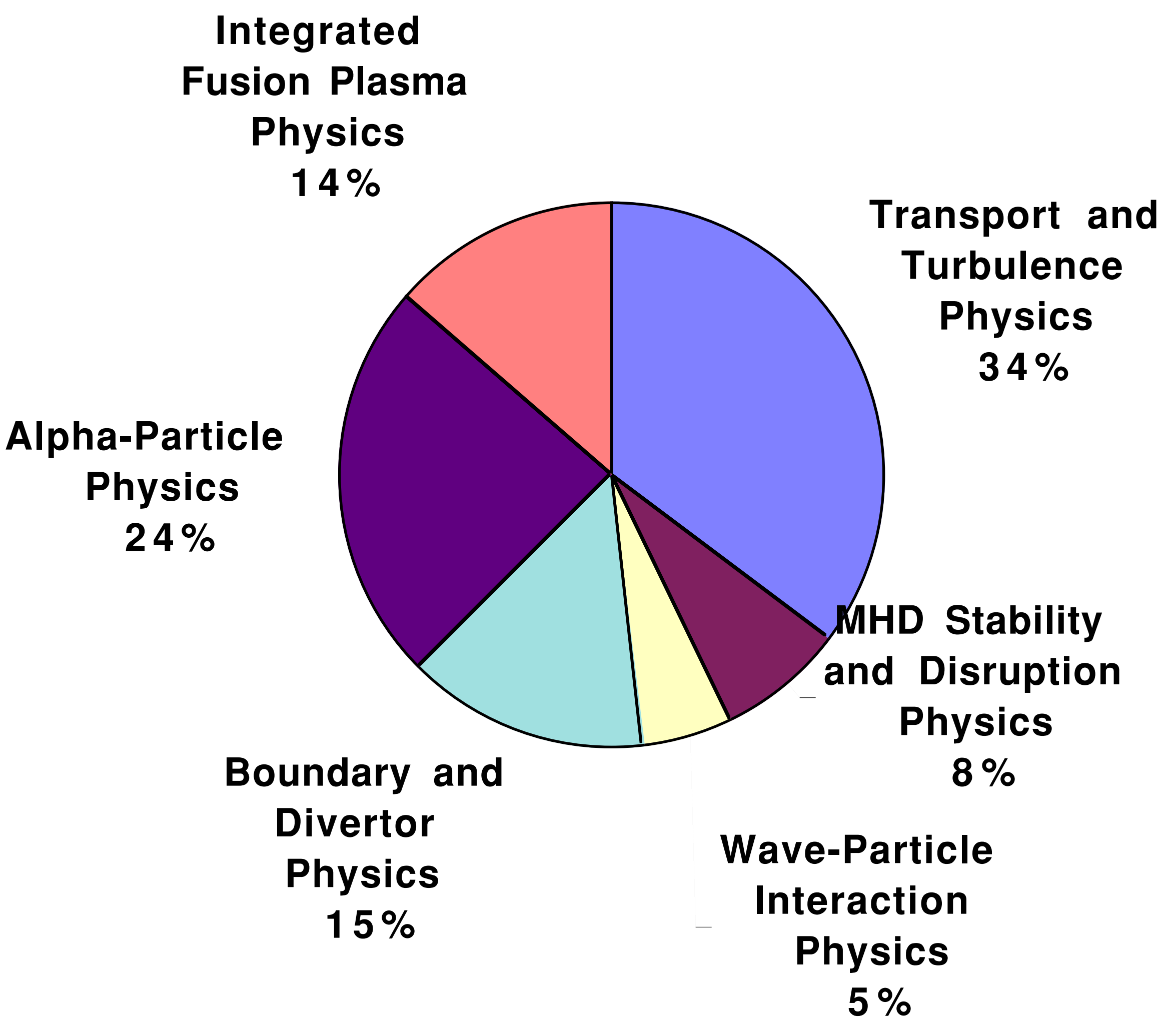

Figure 2. Distribution of the $8M of FY99 international collaborations activity in the tokamak program

In the tokamak program, the activity totals roughly $8M and is divided among physics topics are shown in the pie chart of Figure 2. Transport, energetic particle effect, and integration/concept optimization are the areas of primary emphasis. The largest components of the work involve collaborations with the largest tokamaks, JET (~$3M) and JT-60U (~$2M); participation on smaller devices was significant. JET is unique for its DT capability for energetic particle studies, but the US collaborations also involve “advanced tokamak”, transport, stability, power/particle-handling, and wave-particle interaction studies utilizing US systems and personnel in key roles. JT-60U activity addresses optimization studies in transport and stability. Many of the collaborations involve coupling with the domestic tokamak programs, with size-scaling experiments in key areas being prevalent.

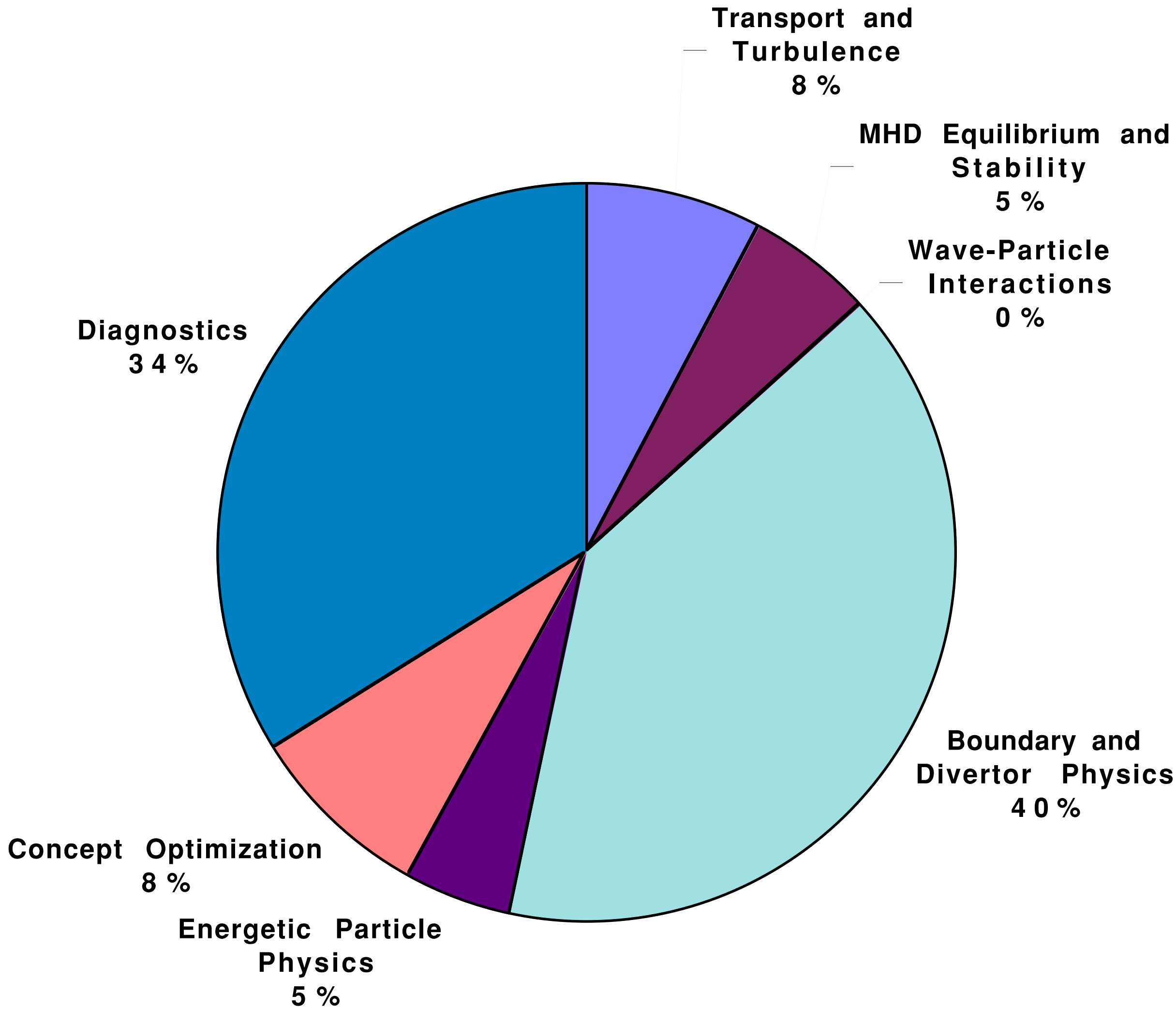

Figure 3. Distribution of the $2M of FY99 international collaborations activity in the alternate/innovative concepts area program

In the alternate/innovative concepts area, the budget is roughly $2M and is spread across the topics shown in the pie chart of Figure 3. The major activity is on the LHD stellarator in Japan, with a total of ~$1.5M.

In the inertial fusion energy area, where the budget is roughly $0.4M, most of the international collaboration is in the area of heavy ion driver development, including design of ion bunching hardware and examination of plasma lens concepts.

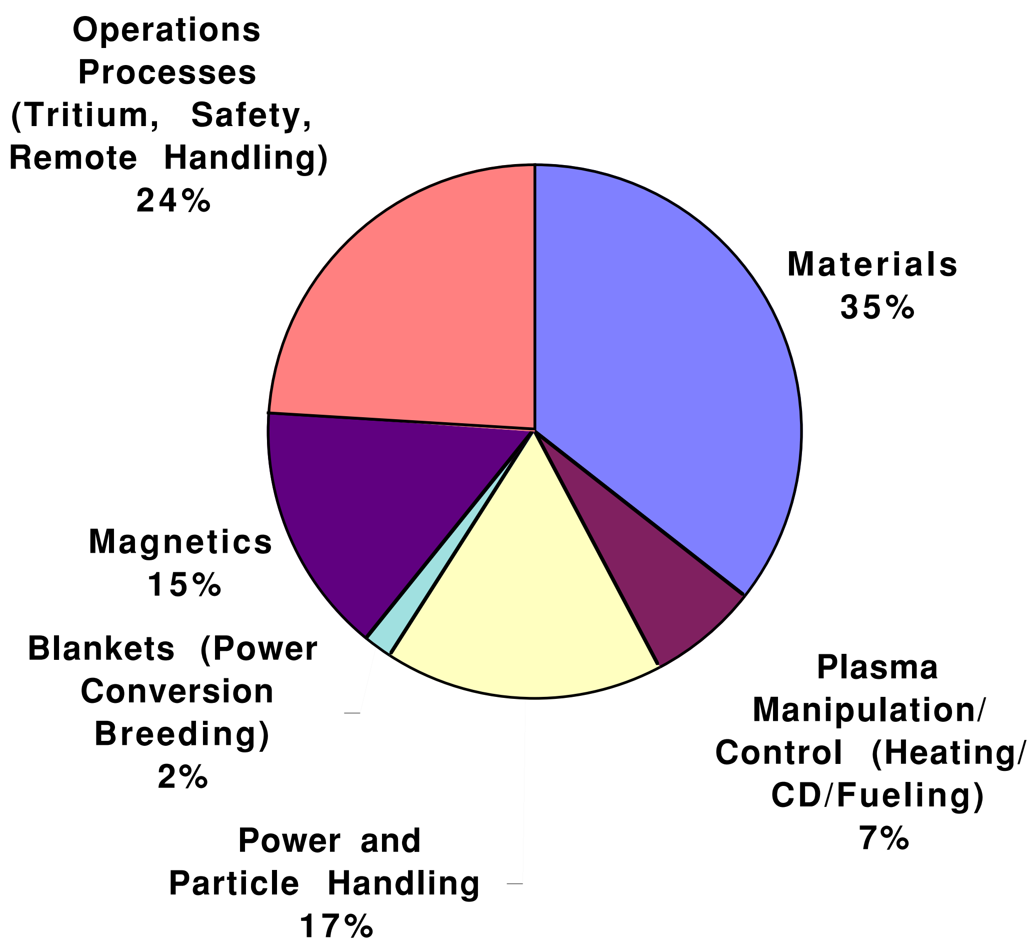

Figure 4. Distribution of the $14M of FY99 international collaborations activity in the technology program

In the technology area, where the budget amounts of roughly $14M, the effort is divided among the areas as shown in the pie chart of Figure 4.

i) In the materials, area, which is the largest effort at roughly $5M, the dominant effort is in the study of irradiation effects on structural materials, mostly in collaboration with the Japanese JAERI and Monsbushu programs, where there is equal cost sharing between the US and Japanese Monsbusho programs at the level of roughly $2.5M each.

ii) In the tritium/safety/remote-handling area, where there is roughly $3.5M, the dominant elements are the tritium systems developments and operations of the TSTA at Los Alamos jointly with Japan, and tritium studies related to the TFTR D&D activities.

iii) In the power and particle handling area, where there is roughly $2.5M, the major elements include completion of the divertor cassette, tritium retention studies on JET and the Japanese Tritium Plasma Experiment, high heat flux testing with JAERI, and erosion/redeposition and high heat flux testing on LHD.

iv) In the magnetics area, where there is roughly $2M, the dominant activity is the completion of fabrication and then installation and test of the Central Solenoid Model Coil at Naka, Japan.

v) In the heating/current drive, and fueling area, which totals roughly $1M, the primary areas are development of RF (ICRF on JET and LHD, Lower Hybrid on LHD, and ECH on LHD) and fueling physics and technology (pellet injectors on LHD and Tore Supra).

vi) In the blanket area, where there is roughly $0.15M, activities include design of a test module for the blanket testing program and neutronics studies of low activation materials, nuclear heating and code validation as part of the IEA cooperative program.

3. Directions and Opportunities

This section expands on the current status of the international collaboration programs in each of the major topical areas, and then describes the opportunities where the US fusion program issues could be well addressed by future international collaborations. The following five sections describe opportunities and recommended directions for future international collaborations in the areas of burning plasmas and tokamaks, innovative/alternate concepts, inertial fusion energy, theory, and technology.

3.1. Burning plasma and tokamaks

Recent years have seen striking worldwide progress in tokamak fusion research which have impacted tokamak power plant concepts, generated new research strategies, and contributed to the general scientific knowledge base applicable to other fusion concepts. This progress has been facilitated by international collaboration.

U.S. tokamak research emphasizes fusion science with a central theme of innovative concept improvement with priority physics research to be carried out in six areas:

1. Transport and turbulence physics is the processes by which heat and particles transport across the magnetic field and thus degrade confinement and limit performance. The tokamak research objective is: improve the understanding of energy and particle transport processes and physics-based predictive scaling to next step tokamaks.

2. MHD stability and disruption physics is the study of the macroscopic plasma behavior determining the equilibrium plasma and its stability to large-scale instabilities which might disrupt confinement. The tokamak research objective is: develop understanding of high beta ideal and nonideal magneto-hydrodynamic (MHD) stability limits through detailed theory-experiment interaction. This includes disruption avoidance and mitigation.

3. Wave-particle interaction physics are the processes by which energetic beams or radio frequency waves can be used to heat or drive current in the plasma and the process by which the plasma can be fueled. The tokamak research objective is: demonstrate efficient current profile control, utilizing external sources to complement the intrinsically driven bootstrap currents, benchmarked with predictive modeling

4. Boundary and divertor physics is the science of the transition between the confined plasma core and the wall, plasma/atomic physics, plasma flows, and neutral particle interactions. The tokamak research objective is: demonstrate, and predictively model, the divertor dissipation of intense power fluxes, plasma flow, pumping of helium ash, and the baffling of recycling neutral particles.

5. Alpha-particle physics is the study of the processes that the energetic charged fusion products encounter while transferring their energy to the confined plasma. The tokamak research objective is: carry out experiments with D-T

fusion reaction products and with energetic ions to benchmark alpha particle physics.

6. Integrated burning plasma physics is research integrating the above research topics on optimizing the tokamak. The tokamak research objective is to reduce the size of a steady-state tokamak power plant.

World Wide Tokamak Research

During the next decade when a burning plasma facility could be built, tokamak fusion science research will be carried out mainly with existing facilities with modest upgrades and with extensive international collaboration. The smaller U.S. tokamak facilities carry out frontline research by means of their facilities' flexibilities, innovation, and diagnostic capabilities coupled to U.S. strengths in theory and modeling. Tokamak research in the 2000 decade will emphasize understanding and optimization through experiment-theory interaction across the whole spectrum of fusion plasma physics.

Advanced tokamak research will be a central U.S. research during the next decade. This will consist of deepening understanding of a broad range of physics areas, extending the tokamak performance boundaries, and extending their pulse length. This research, coupled to benchmarked theory and modeling, will contribute to the knowledge base for an attractive fusion power source.

Worldwide tokamaks have characteristics (listed in Table I) and research programs which differ and complement each other. These facilities provide opportunities for scientific confirmation, collaboration, and joint experiments. Likewise, a large number of foreign scientists collaborate on U.S. tokamaks. The combination of results from foreign devices will form the basis for a major next international step along the tokamak line. Since the U.S. intends to have a significant role in developing next-step tokamak activities, the U.S. tokamak program collaborates on tokamaks abroad. Two large tokamaks now operate: the European JET can operate with D-T plasmas, while the Japanese JT-60U research focuses on steady-state high-performance plasmas.

There are five mid-size tokamaks in the world equipped with sufficient plasma heating, control, and diagnostic systems to advance tokamak research on a broad front. The U.S. tokamaks, DIII-D[18] and Alcator C-Mod[19] operate as national collaborative programs. DIII-D is a highly-shaped low-field tokamak with high power heating including ECH for high-beta advanced tokamak research. DIII-D is unique worldwide with its poloidal field magnet capability for very high plasma shaping and its ability to emulate other tokamak shapes for coordinated joint experimental studies. Alcator C-Mod is the world's highest-field tokamak, capable of very high-density operation, with plasma pressure equal to that expected in a reactor. Its compact size and closed divertor configuration offer unique capabilities for studying high power-density plasma exhaust problems. Together DIII-D and Alcator C-Mod provide data from two plasmas with very different physical parameters but more similar dimensionless parameters. The German ASDEX-Upgrade has external plasma shaping control coils and different divertor geometry. Its research focuses on divertor and advanced tokamak research. The French Tore-Supra is a circular superconducting tokamak investigating the physics of steady-state current drive and heat removal with an ergodic-magnetic-limiter. FT-U is a high field circular tokamak equipped with several additional power systems; its research focuses on high density operation, profile control and transport barriers with strong electron heating. The U.S. also collaborates with several smaller tokamaks listed in Table 1. Italy is constructing a high field ignition experiment—Ignitor. Korea and China are designing superconducting advanced tokamaks (KSTAR and HT-7U) to begin operation circa 2003.

Strategic International Collaboration Opportunities In Burning Plasma Physics And Tokamak Performance, Including Tokamak Concept Innovation

1. Burning Plasma Physics Collaboration:

   With the shutdown of the TFTR experiment, the U.S. has no facility capable of D-T operation. The European Union JET facility in England is the only magnetic fusion facility now capable of D-T operation. Possible new facilities for future burning plasma physics research include the evolving ITER process and the Italian Ignitor tokamak.

2. Advanced Tokamak Physics Collaboration:

   The advanced tokamak is a new innovative concept for tokamak optimization leading to a more attractive power plant and to reduced cost next steps. The discovery of transport barriers has fundamentally altered our understanding of energy containment in magnetic fusion systems. Energy transport and turbulence have been greatly reduced, to the theoretical predicted minimum. While capitalizing on the improved confinement, international tokamaks are also extending the MHD stability limits, increasing the bootstrap fraction, and discovering ways to handle high power divertor exhaust in what is called the advanced tokamak concept. The U.S. tokamak program is keenly engaged in AT research. Collaboration with JT-60U, JET, ASDEX-Upgrade, TEXTOR, FT-U, and TCV will accelerate advances in physics understanding. This line of research is also being pursued in the evolving reduced cost ITER concept with which the U.S. should seek to be involved.

3. Topical Collaborations in Size Scaling:

   Collaboration on the largest tokamaks, JET and JT-60U, provide opportunities to extend understanding beyond smaller size U.S. tokamaks. Tokamak physics collaborations are now carried out via experiment and/or theory collaborations on well defined specific topics. The international expert groups and databases form a very effective vehicle for coordination and focusing these collaborations.

Present International Collaboration On Tokamaks

International tokamak collaboration is supported by both direct funding from DOE (approximately $4.5M per year for tokamak physics and $1.5M per year for diagnostics) and activities supported by major programs such as DIII-D and Alcator C-Mod or by laboratory and universities (approximately totaling $0.9M per year). In addition, international workshops and international expert physics working groups are being undertaken at an estimated level of approximately $0.9M, again encouraged, approved, and implemented by individual programs. Direct funded collaborations are initiated by field work proposals and grant proposals. Other collaborations are conducted with program funds by facility directors to optimize their overall program accomplishments with oversight by program advisory committees and DOE.

The major international collaboration during the past nine years has been the conceptual and engineering design of ITER. Three parties are proceeding with a reduced cost design but the U.S. Congress has not allowed U.S. continued participation, other than to complete prototype engineering testing. ITER very effectively brought together physics experts on a voluntary basis to coordinate research, assembly of data bases, critical peer review of research, and prioritization of research issues. U.S. participation will continue in physics R&D activities.

<u>Opportunities For New Tokamak International Collaborations</u>

Beyond these present collaborations, several potentially valuable additional international tokamak collaboration proposals have been identified by the tokamak subgroup which should be considered for initiation in FY99. We did not have formal proposals nor complete descriptions on the possible opportunities and therefore did not carry out technical reviews. Funding levels were proposed by the advocates and not reviewed by the tokamak subgroup. The working group is not proposing that these new opportunities are more valuable than needs within the presently very constrained U.S. tokamak program. Nevertheless, we did identify and recommend opportunities for new collaboration in three general areas:

- JET D-T collaboration including improvements to the JET ICRF system and in TAE mode studies.

- Collaboration on new next step international tokamaks including Ignitor, KSTAR, and HT-7U.

- Diagnostic collaborations on JET and TEXTOR.

Funding these collaborations should not be at the expense of further weakening our domestic program. Seven new specific collaborations have been identified:

1. Collaboration on JET ICRF System Improvement:

Plasma operations on the JET tokamak will provide the only opportunity in the near term for the U.S. to participate in physics studies on a reactor grade, deuterium-tritium plasma. Several factors contribute to making a collaborative endeavor in RF physics and technology on JET particularly appropriate for the U.S. program. JET operations have long demonstrated a commitment to using RF-based heating technologies to reach high fusion performance goals. However, to fulfill the ambitions of attaining larger Q values in long-duration AT regimes will require more effective coupling of RF power to the plasma than is presently possible. Presently only 8 of 32 MW transmitter power is coupled. The aim of this joint collaboration would be to increase the coupled power to 12-16 MW.

A significant difficulty in raising the core energy density lies in the strongly varying edge conditions present in the ELMing H mode targets. The proposal will provide JET with RF tuning, matching and ELM protection circuitry that will yield a cost-effective means of significantly improving their coupling, and therefore their overall plasma heating capabilities. A successful collaboration in this area will provide high leverage for the U.S. program, as it will create a path for direct involvement in the JET physics program in an area that is of high visibility and central to their operations and ultimate technical success with and wothout D-T plasmas. Experience gained can be of general benefit. Given the rapidly changing situation with the JET physics staff and organizational structure, the timing of making such an collaborative investment is also optimal.

2. Collaboration on JET Research on Alfvén Eigenmodes and Fast-Particle-Wave Interaction:

The experimental project proposed for the MIT-JET collaboration is aimed at studying the interaction between non-thermal plasma particles and electromagnetic waves in the Alfvén range of frequencies on the JET tokamak. The interaction between plasma waves and fast particles such as fusion produced alphas is one of the critical issues to understand the behavior of burning tokamak plasma and can be studied on the reactor-relevant JET plasmas. The extensive set of active and passive diagnostic systems specifically developed for the study of wave-particle interaction in the Alfvén Eigenmode range of frequencies is now fully operational and available. These systems include the saddle coil exciter, capable of exciting and tracking low-toroidal modes and to measure frequencies, mode structures and damping rates, and a fast magnetic fluctuation diagnostic recording. This collaboration would include a post-doctoral fellow full time on the JET site.

3. Collaboration on Ignitor:

Other than ITER, Ignitor is the only presently funded MFE project in the world aimed at the production and study of burning plasmas. Based on the high-field, high-current density tokamak approach. Ignitor will likely be the first facility to operate with reactor-like non-dimensional plasma parameters, including gyrosize, and should therefore provide critical tests of relevant plasma physics as well as addressing issues specific to alpha-heating and fusion burn. U.S. collaboration would provide an opportunity for participation in this important and relevant research, and enhance and strengthen the Ignitor program through the application of expertise developed in the U.S. program. Specific near-term opportunities for U.S. participation include: design activities with respect to the ICRF system; modeling and theory efforts including analysis and simulation of ignition scenarios; design of a pellet injection system for fueling and profile control; engineering analysis; and modeling of plasma-wall interactions. Additional opportunities exist for design and deployment of diagnostics, including alpha-particle diagnostics, to enhance the Ignitor physics program. Such a collaboration could also explore and define viable advanced tokamak and high Q scenarios for Ignitor and provide support for simulations and theory for extrapolating the results of the Ignitor program. This extended program would further the understanding of advanced tokamak modes of operation, including transport barriers, profile control, and beta limits in high Q burning DT plasmas. Several workshops are being organized to be held in early FY99 to address the range of potential collaborations with Ignitor; these should lead to specific technical proposals for collaborations and contribute a more in-depth understanding of the scientific and technological capabilities of the Ignitor facility.

4. Collaboration on KSTAR:

The KSTAR tokamak is being constructed by Korea to extend the performance and pulse length of the advanced tokamak (AT) concept as a step toward an attractive tokamak reactor. The project has successfully completed a series of reviews and has moved into the engineering and construction phase. A U.S. team has contributed to the KSTAR design under Korean funding, and this collaboration is expected to continue. While Korea will assume full responsibility for constructing and operating the basic tokamak facility, it openly welcomes collaborating countries to contribute ancillary hardware and participate as partners in the experiment. A U.S. collaboration on KSTAR, including substantial U.S. hardware contributions, has been proposed. Its main focus would be the physics and technology of AT profile control and sustainment. The benefit to the U.S. would be an understanding of the role of current-profile control in increasing tokamak plasma performance and pulse length on time scales long compared to current relaxation times. Also the U.S. would develop technologies (radio frequency wave launchers and diagnostics) critical to AT plasma control, and implement and test them on an advanced tokamak facility whose pulse length (20-300s) greatly exceeds those available on today's AT experiments. In return for hardware contributions U.S. researchers would gain access to the experiment and a voice in the planning the research program. The first year program (FY-99) would include technical exchanges (on remote collaboration, profile control requirements, AT experiments, diagnostics) to prepare the foundation for such a program before making hardware commitments.

5. Collaboration on HT-7U:

The Chinese government has approved the construction of a superconducting advanced tokamak. HT-7U is at an earlier stage of development than KSTAR. It will be built and sited at the 600-person Institute of Plasma Physics, Academia Sinica in Hefei, China. To encourage collaboration, the institute has 20 positions from China's national visiting scholar program available to support engineers and scientists with expenses and salary to live very well in China. Operation is planned to begin in about 5 years. HT-7U will be a superconducting tokamak with R = 1.6 m, a = 0.35 m, b/a = 2 at 3.5 T, and a plasma current of 1 MA. Like KSTAR it is a slightly smaller version of TPX. It will have 4-8 MW of ICRF/LHCD and 1 MW of ECRH. Pulse length will range from 60 s to continuous. It will include advanced tokamak features, current drive, and divertor. They are seeking approval to use existing superconducting cable from the canceled SSC project.

6. Collaboration on JET Intense Diagnostic Neutral Beam:

This project proposes to develop, and demonstrate the advantages of an intense, rep-rated diagnostic neutral beam for large-scale plasmas. The project divides into three main tasks: (1) Creating a hydrogenic ion beam source with ~10kA of current at 100-250keV, for 1 microsecond duration, with sufficiently low beam divergence; (2) mating it to a neutralizer cell and suitable beam line with pumping system, and finally; (3) installing on JET or some other large, moderate-to-high density tokamak where it can aid in full profile charge exchange recombination and Motional Stark effect measurements. A three-year timescale is envisioned. The source work extends a three-year diagnostic development effort from the early 1990's at LANL, and a three-year "Continuous High-Average Microsecond Pulser" (CHAMP) LDRD project for plasma processing. Preliminary discussions between LANL, Princeton, and JET have been made. A rough division of effort with LANL developing the source, PPPL developing the beam line, and JET working the interface and spectroscopy issues were discussed.

Table 1

CURRENT ACHIEVED OR DESIGN PARAMETERS OF WORLD TOKAMAKS

	R(m)	B(T)	I(MA)	COMMENT
POWER PLANT CONCEPTUAL DESIGNS				
ARIES-RS	5.5	8.0	11.3	U.S.
SSTR	7.0	9.0	12.0	Japan
FUSION ENERGY DEVELOPMENT FACILITY DESIGNS				
(ITER-EDA)	8.1	5.7	21.0	Superconductor (superceded)
RTO/RC-ITER	~6.4	~4.2	~17.0	Evolving ITER design
BURNING PLASMA EXPERIMENT DESIGNS (DTAT variants)				
(BPX)	2.6	9.0	12.0	U.S. Copper (cancelled)
IGNITOR	1.3	13.0	12.0	Italian-Copper proposal
FIRE	~2.0	~10.0	~8.0	Evolving U.S. next-step study
(JT-60SU/ATBX)				JAPAN/U.S. (DESIGNS)
STEADY-STATE SUPERCONDUCTING ADVANCED TOKAMAK DESIGNS (SSAT variants)				
(JT-60SU)	5.0	6.25	10.0	Japan (inactive design)
(TPX)	1.8	4.0	2.0	U.S. (cancelled)
KSTAR	1.8	3.5	2.0	Korea (under construction)
HT-7U	1.7	3.5	1.0	China (under design)
OPERATING PERFORMANCE EXTENSION TOKAMAKS				
JET	3.0	4.0	6.0	E.U.
JT-60U	3.3	4.4	3.0	Japan
(TFTR)	2.48	5.8	3.0	U.S. (shutdown)
DIII-D	1.7	2.1	3.0	U.S.
Alcator C-Mod	0.65	9.0	2.0	U.S.
Tore Supra	2.3	4.0	1.7	France (superconducting)
ASDEX Upgrade	1.7	3.1	1.6	Germany
OPERATING PROOF OF PRINCIPLE TOKAMAKS				
FT-U	0.93	8.0	1.6	Italy
TCV	0.88	1.4	1.2	Switzerland
TEXTOR	1.75	3.0	1.0	Germany
T-10	1.5	3.0	0.4	Russia
Compass-D	0.55	2.1	0.4	England
Triam-1M	0.84	8.0	0.15	Japan (superconducting)
CONCEPT EXPLORATION TOKAMAKS				
JFT-2M	1.3	2.2	0.5	Japan
Tuman-3M	0.5	1.2	0.18	Russia
HBT-EP	0.95	0.35	0.025	U.S./Columbia U.
(LCT-2)	5.0	0.5	0.3	U.S./UCLA (1999 startup)

3.2. Innovative concept developments

Research on stellarators, spherical tori (ST's) and reversed field pinches (RFP's) advances our understanding of toroidal confinement in the direction encouraged in the present U.S. Fusion Energy Sciences Program. The physics of these innovative MFE concepts is closely related to that of Tokamaks (Section 1), and can be organized by similar topics: transport and turbulence; MHD equilibrium and stability; wave-particle interactions; boundary and divertor physics; energetic particle physics, concept optimization, and diagnostics. A high level of collaboration is expected for stellarators because of the very large foreign investments and device capabilities in this area relative to that in the U.S. program. U.S. experiments in the spherical torus (NSTX) and RFP (MST) areas are growing and are more capable or comparable to those in other countries. New collaborations on these concepts are expected to begin in FY-99.

Stellarators (Helical Systems)

The prime focus for collaboration on foreign stellarators is the billion-dollar-class steady-state Large Helical Device (LHD) in Japan because its order of magnitude increases in plasma volume, heating power, and pulse length over that in existing stellarators allow studies of size scaling and stellarator physics at more reactor-relevant parameters (beta ≥ 5%, ion temperature ~ 10 keV, energy confinement times of hundreds of ms, etc.), close to that accessible in present tokamaks. LHD's superconducting coil system, magnetic-island-based divertor, and steady-state multi-MW heating power also allow comparison with steady-state component development in tokamaks, as reflected in the Technology collaborations (Section 5). More modest ($50-100 million scale) stellarators in Germany (W7-AS) and Spain (TJ-II) allow studies of confinement improvement, configuration optimization, and divertors in magnetic configurations complementary to that of LHD. The wide range of stellarator configurations accessible on LHD, W7-AS, and TJ-II allow study of the role of aspect ratio, helical axis excursion, magnetic-island-based divertors, and the consequences of a net plasma current, elements that are being incorporated in low-aspect-ratio stellarator concepts under consideration in the U.S. program.

Understanding *anomalous transport and the underlying turbulence* is essential for the confinement improvement needed for the viability of the stellarator concept. Installation of imaging bolometer and fast visible imaging systems on LHD allows understanding of the radiative power balance, the plasma shape, and MHD instabilities. Digital holography and multi-channel H-alpha diagnostics would allow modeling of pellet ablation in non-thermal toroidal plasmas important for pellet fueling and for profile control. These studies can be extended with pellet injection on the low-shear W7-AS stellarator for detailed study of particle transport as well as maximizing plasma parameters and central fueling with an island-based divertor. Advantage can be taken of the U.S.-supplied neutral beams on TJ-II to compare MHD beta limits, transport, and fluctuations in the high-transform low-shear large-helical-axis TJ-II with the medium-transform high-shear planar-axis LHD and the lower-transform low-shear planar-axis W7-AS.

Better understanding of *MHD equilibrium and stability* is needed to increase beta values from the present 2% level to >5%. Installation and use of 3-D low-profile magnetic probes and accompanying MHD analysis will allow improved MHD studies in stellarator plasmas, and modeling of nonlinear MHD and electric field effects would extend our understanding in these areas.

ICRF heating and ECH are important as complements to NBI in stellarators because these *wave-particle interactions* do not deposit particles in the plasma and preferentially heat perpendicular to the magnetic field. Experiments and modeling of fast wave, mode conversion, and IBW heating with folded waveguide and single loop antennas and the resulting ICRF physics allows improved ICRF heating scenarios for toroidal devices as well as operational experience for the U.S. program on stellarators. Diagnostics and modeling to study ECH power launch polarization, mode coupling, and deposition would allow improved ECH modeling capabilities for DIII-D and U.S. stellarators.

Better understanding of *boundary and divertor physics* is needed for effective particle and power handling in stellarators; the U.S. will rely on assessment of LHD's magnetic-island-based divertor for the low aspect ratio stellarator concepts under consideration in the U.S. program. Study of edge/boundary physics and plasma-materials interactions in LHD is important for developing understanding of unique boundary plasma physics and developing new material solutions for steady-state plasma devices (see Technology collaborations in Section 5).

Understanding of *energetic particle physics* is important in stellarators because the helical magnetic field ripple could lead to increased neoclassical transport and direct loss of energetic particles. 1-D and 2-D scanning neutral particle analyzers will be installed on LHD to study the thermal and fast ion confinement, the NBI fast ion distribution and resultant heating, and reduction of energetic orbit losses. Direct measurement of the fast particle loss region will be made with fast particle collectors mounted in both LHD and W7-AS for comparative studies with earlier measurements on the Japanese CHS stellarator.

An important goal of stellarator research is *configuration optimization*. Development and benchmarking of bootstrap current codes, ballooning stability codes, kink stability codes, and free-boundary equilibrium codes for evaluation of flux surface integrity on LHD and W7-X is important for application to proposed, highly optimized, U.S. stellarators.

Experimental understanding depends on the proper *diagnostics*. Demonstration of an MDS-plus data acquisition system on LHD is important for long-pulse operation as well as better data acquisition and control of U.S. diagnostics on LHD.

<u>Spherical Tori</u>

With the approaching research programs of NSTX and Pegasus and the upgraded capabilities in HIT-II and CDX-U, the U.S. can compete and lead the world in ST research. The international ST collaborations therefore emphasize areas of complementary capabilities and expertise. The world ST community is growing with the planned addition of new devices by the end of 1998: MAST in U.K., Globus-M in Russia, TS-4 in Japan, and ETE in Brazil. The combined, advancing expertise and resources make realistic the prospect for establishing the Proof-of-Principle database for ST's during the next 4-5 years.

The ST collaborations recommended in the attached Table amount to about $1M per year in the near future. The FY-99 collaborations will largely be new (incremental) activities, as the world ST research advances into the Proof-of-Principle stage. We assume that only ~3% of the resources applied to ST research in the U.S. should be applied to international collaboration, to be focused in areas of high leverage and cost effectiveness. The ST recommendations presented in the attached Table satisfy this criterion.

The key issues of interest for ST collaborations are well defined by the unique potentials of the ST plasmas. In Transport and Turbulence, collaboration on the establishment of strong transport barriers is emphasized, taking advantage of the expected strong sheared flow driven by diamagnetic drift associated with order unity beta in the ST. In MHD Equilibrium and Stability, joint investigations of stabilizing mechanisms for MHD, resistive, neoclassical, and fast-particle-driven modes should promote rapid progress. In Boundary and Divertor Physics, sharing of modern tools of analysis will accelerate understanding of this complex topic of high importance to future ST applications. In Energetic Particle Physics, collaborations in neutral beam and modern research tools leverage existing equipment for rapid progress. In Diagnostics, highly advanced techniques already developed in Russia should contribute greatly to advancing our understanding of the ST plasma in a very cost-effective manner.

Reversed Field Pinches

The world RFP experimental program consists mainly of four experiments: MST in the U.S., RFX in Italy, TPE-RX in Japan, and T2 in Sweden. The first three are of similar size, allowing joint experiments and effective comparisons in confinement improvement and scaling. Modest base collaborations focus on joint work on plasma optimization (TPE-RX); pulsed poloidal current drive, current profile control, and locked modes (RFX); and resistive wall instabilities (T2). A larger base program involves installation of a diagnostic neutral beam on MST from Novisibirsk (Russia) to diagnose fluctuations and transport using Rutherford scattering and charge exchange recombination spectroscopy. An outstanding opportunity in the RFP area is to extend this collaboration to plasma heating with neutral beams for confinement and beta limit studies. The Novosibirsk group would construct the beams and participate in physics experiments on MST.

Other Innovative MFE Concepts

Opportunities exist for productive collaborations for other innovative MFE concepts (spheromaks, FRC's, etc.) but the low level of support for these concepts limits interactions with their foreign colleagues to short visits and international conferences. The U.S. priority has been on staff and equipment in restricted-budget innovative MFE programs rather than on international collaboration.

3.3. Inertial Fusion Energy (IFE)

International activities on Inertial Fusion Energy (IFE) have been limited in the past due to DOE classification and policy. In December 1993 all target physics experiments relevant to IFE were declassified. Furthermore, several independent expert reviews have recommended that international collaborations in IFE be encouraged. As a result of these changes some bilateral international activities are beginning and an initiative to establish a multilateral approach to IFE has begun.

Target Physics

The most important issue for IFE is whether sufficient energy gain can be obtained in either a direct or an indirect drive target with a low enough driver energy that an economic power plant of "reasonable" size can be built. The baseline direct and indirect drive targets both rely on compression and central hot spot ignition to achieve high gain. Most ICF facilities around the world are addressing this fundamental question, for the baseline target concept, in one form or another. An alternate target design, called the fast igniter concept, uses separate compression and ignition drivers. One driver compresses the fuel to high density but does not need to create a central hot spot, while the other driver ignites a spot on the edge of the cold, compressed fuel ball. The compression driver can either be an ion or laser beam. The ignition driver must be an extremely short pulse, high power driver. Laser technology has been developed that is suitable for this approach and concepts are being explored for ion drivers.

The fast igniter concept can potentially achieve higher gain at lower drive energy than the baseline, central ignition targets. For example, it is estimated that gain of about 300 for about 1.2 MJ of drive energy could in principle be demonstrated with the National Ignition Facility (NIF) facility if about 10% of the laser beams were adapted for 20 ps operation using chirped pulse amplification and compression. Nominal indirect drive targets are expected to produce a gain of about 10 at 1.8 MJ on NIF. While there is high payoff for success with the fast igniter, there is considerable technical risk in the approach. As the target is compressed, a hot, dense plasma forms around the compressed core. There is great uncertainty about whether the high intensity, short igniter pulse can penetrate this plasma to deliver sufficient energy in a short enough time to ignite a spot on the edge of the compressed core. This critical uncertainty must be answered before use of NIF for fast ignition experiments can be considered seriously.

The fast igniter concept was originated in the DOE program at LLNL and its leadership in Petawatt laser development has given LLNL a leading role in fast igniter research. The concept has great implications for IFE. There is, therefore, a high level of international interest and expertise in the fast ignition concept.

The Japanese Gekko laser facility, for example, is currently being used primarily for fast igniter research. Gekko has a capability to do 12 beam implosions and is rapidly developing a Petawatt capability for a short pulse igniter beam. This availability of both an igniter beam and target compression capability will not be available in the US after the closure of Nova in May 1999. Collaboration with the Japanese on Gekko is therefore a most timely objective. Several European projects are also focusing effort on fast ignition physics with laser facilities smaller than Gekko but having a high shot rate and high scientific output. Theoretical work, notably PIC modeling is also very advanced in some European groups. In particular, present work at Rutherford Laboratory in the UK and proposed work at GSI in Darmstadt, Germany is oriented toward understanding fast igniter physics sufficiently to evaluate its viability.

Very preliminary discussions with the Japanese, Germans and Rutherford in the UK have taken place. It is attractive therefore to envisage a world wide coordinated investigation of fast ignition with the US adopting formal collaborations with both Japan and Europe.

Funding of $0.5 million in FY99 and $1.0 million in FY00, 01, and 02 would enable this collaboration to be established early in FY99 so that it would be operating fully by the time that Nova is shut down. The collaboration in FY99 would fund U.S. staff to participate in joint theory work with all organizations and joint experiments at Gekko and the facilities at Rutherford in 1999. In FY00 joint experiments would continue on Gekko and at Rutherford, while work with GSI would help establish an experimental capability there. The leverage of this small investment at this time would be very high as it would allow the U.S. to remain in a leadership position in fast igniter physics at a time when there is a hiatus in experimental capability in the U.S. If this collaboration is not developed, the Europeans and Japanese may develop collaborations independent of the US leaving the fast igniter effort in the US isolated and in a sub-critical condition. IFE, therefore, proposes the fast igniter collaboration as the "new initiative" for the near term.

Other IFE target physics collaborations are within the baseline program and would be funded with existing funding sources. Two collaborations with GSI on conventional heavy ion target physics and high energy density physics are currently being pursued. The objectives are to jointly exploit GSI's high intensity heavy ion beam to measure heavy ion stopping in hot dense plasmas created by a laser, which LLNL will help design and to explore ways to use the high energy density plasmas they can create for basic physics measurements.

Heavy Ion Driver Development

Four collaborations are being pursued to further the development of heavy ion accelerators so that they will have the characteristics necessary to drive conventional IFE targets. All are within the baseline program of international activities.

A scientist from the U.S. heavy ion fusion program is on assignment at GSI on a joint program to design ion bunching hardware to add to the GSI accelerator to produce a more intense beam. This collaboration is also examining the feasibility of the plasma lens concept. Both these efforts would be of value both for the RF driver concepts the Germans are pursuing and for the induction accelerator concepts the U.S. is pursuing.

An incoming collaboration involves a visiting scientist from GSI working with scientists at LBNL and LLNL on calculations of channel transport and plasma lens operation. These combine the ideas of the two largest HIF groups in the world and may lead to joint experiments.

The Russians have proposed to increase the energy and intensity of their heavy ion accelerator at ITEP in Russia and our scientists are having discussions with ITEP scientists about collaborations. These discussions are in a very preliminary stage.

A small collaboration exists with the Japanese to pursue their efforts to reduce the price of ferromagnetic cores. This would increase the attractiveness of HIF.

Laser Driver Development

Two sizable collaborations on solid state laser development have been ongoing with France and Britain for some time and a new effort with Japan is just beginning. All are within the baseline program and are currently being funded within Defense Programs.

The largest international activity in ICF is the US/France collaboration on the laser and other underlying technology necessary to build the NIF and the Laser MegaJoule (LMJ). The latter is a NIF sized facility the French are building near Bordeaux. The present collaboration is a $300 million joint effort. To date, the French have transferred significant funds to the United States and have agreed to co-fund laser glass manufacturing companies (whose factories are in the U.S.) to install the production equipment that will produce the laser discs for both NIF and LMJ. They have jointly funded much of the component development effort and facilities and have done experiments at LLNL on Beamlet, at the amplifier development laboratory and in the fast crystal growth laboratory.

The British have collaborated with the U.S. on high energy density physics experiments using laser facilities in the U.S. and the U.K. for many years. They are currently considering upgrading the size of their laser facilities and LLNL is collaborating on the design of that upgrade (which would use elements of the NIF design and would involve UK procurement of optical components from U.S. companies). The UK is also designing one of the diagnostic manipulators that will emplace target diagnostics on NIF. The nature of UK collaboration on future NIF experiments is also under discussion.

Both Japan and the U.S. are developing diode pumped solid state lasers (DPSSL) as a driver for an IFE power plant. The two design concepts are quite different as are the diode manufacturing capabilities in the two countries. Discussions have begun under an existing bilateral collaboration that would allow both countries to benefit from the different approaches taken.

Power Plant Technology Development

As mentioned above, the Japanese are vigorously pursuing the fast igniter concept and are rapidly developing excellent Petawatt laser capabilities. They have become interested in a U.S. idea for a neutron source for fusion materials development that is based on the use of a short pulse laser to generate the neutrons in driven (but not ignited) targets. Initial discussions on this topic have been held but there is not yet a firm plan for such a collaboration.

The U. S. has circulated a “draft for comment” proposal to its partners in the IEA collaboration on fusion energy. The thrust of this proposal is to expand the multilateral IEA fusion activities to include IFE. The proposed expansion would involve adding IFE scientist to some of the existing committees (e.g. the ones on fusion materials development and power plant economics) and to establish new committees on topics unique to IFE such as laser and ion beam drivers and target fabrication. Points of Contact (POC) have been named for the U.S., EC, Japan and Russia and first discussions are planned for the meeting in Yokohama this year. If agreement is reached the fusion oversight committee could formally consider the proposal at its January 1999 meeting. If this proposal is implemented, costs for U.S. participation would be included in FY99 and beyond.

3.4. Theory

Goals, Benefits and Implementation

The U.S. theory and modeling research in magnetic fusion has had a long history of international collaborations with our international partners. These include all countries in the European Community, Japan, Russia, Canada, Australia, Korea, China and India. It was recognized early on in fusion energy research that the sharing of methodologies and ideas is an essential stimulus for scientific advances. In the advent of large scale computing, the ability to benchmark complex simulation codes developed independently, often with very different approaches, is an important and necessary step for accuracy and reliability assurance. As magnetic fusion research worldwide moves toward larger experiments which can provide exhaustive details of valuable information, the opportunity to access experimental data to validate theory models and codes, naturally promotes a strong international interaction in theory and modeling as well.

Theory and modeling has received strong, stable support from the OFES. As a result, the U.S. theory and modeling program has established a leadership role worldwide. Any proposal of international scientific exchange involving theory is viewed favorable by our partners as a means to access the wealth of experience in the U.S. theory program. This has facilitated access to data from large foreign experiments, and proves to be a cost effective way for U.S. to remain a leading fusion participant.

Topics of collaboration are typically initiated through discussions among scientists. In cases when urgent answers to scientific issues are needed, collaborations on thematic topics can also be promoted by OFES. Funding for the activities typically comes from the theory base program. An exception may be the provision by OFES of a small amount of travel funds to smaller institutions to offset foreign travel costs. The return for the investment is directly measurable by the large number of joint journal publications and invited talks presented at technical conferences and symposia. To maintain a vibrant theory and modeling international collaboration, its visibility should be elevated both in the scientific review process and in theory grant renewal.

The community proposals can be categorized into five technical topics with major benefits to tokamaks, stellarators, fusion and computational sciences.

Turbulence and Transport

The amount of energy one needs to supply to a fusion machine to produce thermonuclear reaction conditions is directly related to the transport properties of a high temperature plasma. Reducing the required energy is an important goal of fusion research worldwide. It is thus not surprising that understanding the fundamental processes governing transport is a key topic for international researches and forms a common ground for collaboration. A clear focus is on the role of microscopic turbulence on transport. Sophisticated simulation codes running on high performance computing platforms are being used to study the problem

MHD and Energetic Particle Stability

Another topic of common interest is the large scale hydrodynamic behavior of magnetic confinement devices. It controls the stable operation of fusion machines and sets the limit on the energy density of a fusion power plant. Much has been known about short time scale catastrophic behavior when the instability sets in and ways are being explored to avoid them. International researchers are shifting their attention to longer time scale, somewhat weaker instabilities. These instabilities are three-dimensional and rapidly become nonlinear in character. They can limit the energy density and affect transport. They are also similar in many ways to the instabilities which occur in the magnetosphere and present many interesting topics for scientific exploration.

Edge and Divertor Modeling

The edge of a fusion plasma separates a region with extremely high temperature (millions of degrees C) from a material wall a short distance away. It is a region where many simple theoretical assumptions are violated, but also a region rich in plasma, atomic and molecular physics. A challenge to theory is to be able to quantitatively model the heat and particle exhaust from the high temperature region to a much colder region where the energy can be radiated away before reaching the material wall. This is an area where international scientists in plasma, atomic and material science can work together.

Radio Frequency Heating and Current Drive

An efficient way to increase the temperature of a fusion plasma to thermonuclear conditions is using radiofrequency waves. Experimental results have indicated that the heating method can either positively or negatively impact the confinement and stability of the plasma. Theoretical understanding is still lacking and with many large experiments depending on high power rf heating, this is a problem which requires some answers from the international theory community.

Basic Theory and Computational Initiative

Discussions among scientists often lead to identification of basic theory problems of mutual interest. A small fraction of the proposed exchanges falls in this category. This usually results in publications in scientific journals adding to the knowledge base in plasma physics. The recent activities by the DOE to advance a Simulation Science Plan (SSP) has also attracted interest from our international partners. They are cognizant of the potential of a multi-teraflop computing platform in solving challenging fusion problems, not feasible even with state-of-the-art computers. Successful utilization of the next generation high performance computer is a grand challenge in itself. International participation will promote sharing of methodology and ideas which should be very beneficial.

Table 3: Summary of Theory Activities

Turbulence and Transport	**Benefits to U.S.**	**U.S. Instit. or Team**
gyrofluid transport models in Cadarache, W7-X, NAU	tokamak, stellarator	GA, IFS, Maryland, PPPL
gyrokinetic simulations in W7-X, CRPP, FT-U	tokamak, stellarator	Colorado, Maryland, PPPL
drift wave transport in KAIST, SWIP	tokamak	IFS
3-D nonlinear code for ELMS in CIEMAT	tokamak	ORNL
numerical tokamak project in U. Alberta	tokamak	LLNL
ripple & energetic particles	tokamak	PPPL
neoclassical and ITG transport in NIFS, Kyoto,JT60-U	stellarator, tokamak	IFS,NYU
transport barrier confinement in JET, JT60-U,Tore Supra	tokamak	GA, IFS,PPPL
Transport code develop in Kurchatov	tokamak	ORNL
MHD and energetic particles		
energetic particles, TAE in JET, JT60-U, LHD, FT-U	tokamak, stellarator	IFS,PPPL
extended MHD in JT60-U	tokamak	Wisc, GA,PPPL
resistive MHD in Culham, Keldysh Inst.	tokamak	GA,PPPL
edge MHD in Culham, ASDEX-UG	tokamak	GA
advance tokamak stab in JT60-U, KSTAR	tokamak	GA, ORNL,PPPL
equilibrium magnetics in HT7-U	tokamak	GA
nonlinear MHD simulation in Cadarache, CRPP, Moscow State	tokamak, computation	NIMROD, GA
stability of stellarator, heliac in TJ-II Heliac, Univ. Carlos III	stellarator, heliac	ORNL, PPPL
stellarator design in W7-X	stellarator	ORNL, PPPL
Edge and divertor modeling		
modeling of edge fluctuations in IPP Garching, CIEMAT	toroidal devices	Maryland, ORNL
divertor and edge physics in Culham, Novosibirsk	toroidal devices	LLNL, MIT, IFS
UEDGE modeling in POLAND	tokamak	LLNL
L-H transition in stellarator in NIFS	stellarator	ORNL
edge atomic physics in Nagoya	toroidal devices	MIT
RF heating and current drive		
ECH transport simulation in NIFS	toroidal devices	GA

ICRF heating in JET, LHD, KSTAR/KBSI	tokamak, stellarator	Lodestar, ORNL
ICRF edge interaction in JET, LHD	tokamak, stellarator	Lodestar, ORNL
Basic theory and computation		
diagnostics theory in Tsukuba	fusion science	LLNL
basic research - Others	fusion science	IFS,PPPL
MPP computing in CRPP	computation	SSP

3.5. Technology

Materials

Description of Topic:
Fusion must develop materials that satisfy a unique set of performance requirements. Reactor structural materials are subjected to unprecedented neutron irradiation damage levels. Plasma-facing materials also experience extraordinary particle and heat flux loading. These materials must be fabricated into large, complex low activation structures that perform safely with high reliability. Materials developed for other technologies will not meet the needs of fusion.

Description of Tasks:
Low activation structural materials are being irradiated in the BOR-60 reactor in Russia. There are also longstanding collaborations with JAERI and Monbusho on structural materials development. The database on low fluence irradiation of CFC, tungsten, beryllium, and copper alloy heatsinks for plasma-facing components is being completed with Japan, Russia and EU. Finally, joint planning is underway for the International Fusion Materials Irradiation Facility (IFMIF) 14 MeV neutron source.

Benefits to Plasma Science:
For Plasma Science to achieve its ultimate goal of safe, economical fusion energy, there must be corresponding advances in Materials Technology. The Materials Technology community also contributes directly to Plasma Science through the development of new plasma-facing materials, as well as materials for magnets, diagnostics and heating systems.

Rationale for Foreign Collaboration:
Foreign collaboration is required because of the decrease in availability of US irradiation facilities. For example, access to fast reactors is not currently available in the US. Many US irradiation experiments are now carried out in foreign reactors such as the BOR-60 in Russia. Foreign collaborations also allows the US to use non-irradiation facilities such as the JRC Cyclotron at Ispra. Finally, the design of a dedicated 14 MeV neutron source, IFMIF, is an international collaboration.

Major New Opportunities:
A major new opportunity for international collaboration is the IFMIF 14 MeV neutron source for structural materials development. Work has been underway for several years in the preliminary design of this facility.

Plasma Manipulation/ Control (Heating/CD/Fueling)

Description of topic:
The attainment of high-confinement, high-bootstrap-current-fraction, advanced operating modes will require sophisticated control of pressure and current profiles, and the sustainment of these profiles for periods long compared to particle, energy and current transport times. The goal of this topical area is to develop and demonstrate the tools needed to provide flexible, reliable heating, current drive, and particle control (deposition and removal) to the plasma. Without advances in this field, sustainment of the advanced modes desired for future tokamaks will not be possible.

Description of tasks:
The high-priority tasks are:

a) JET: Develop and test improved matching and/or ELM protection circuitry on JET and work with JET rf to improve power-handling capability. In the fueling area, develop high field side pellet fueling capability to provide greater control of particle deposition profile.
b) KSTAR: Develop, build, test, and participate in the operation of a long-pulse ion cyclotron (IC) launcher and a lower hybrid (LH) launcher for KSTAR.

These tasks address two central goals for rf physics and technology: the demonstration of reliable, improved heating and current drive in (nearly) burning plasmas, and the use of ion cyclotron in long-pulse systems to heat, drive current, and control the current profiles to achieve advanced-physics modes of operation. The modest ICRF efforts proposed on Tore Supra, LHD and ASDEX and the existing fueling collaborations on Tore Supra and LHD also support these goals.

Benefits:
The development of improved heating, current drive, and fueling techniques is essential to achieving the operating capabilities that are desired for next generation ignition devices. Reliable, long-pulse control of the power and particle deposition profiles at the required central values, as well as current and density profile control, are needed to operate in advanced-physics operation modes that are proposed.

Rationale for foreign collaboration:
JET: This task provides access to the JET burning plasma physics program and enables development of higher power, higher reliability ICRF systems. The JET rf group is one of the most advanced in the world. They are requesting our collaboration to work on new tuning and matching techniques that will be directly applicable to present and future US experiments. In the fueling area, the existing pellet fueling technology program on high field side launch as well as the ongoing physics experiments/analysis on DIII-D can be leveraged to provide an optimum system for the JET application. The US gets an opportunity to test our development concepts on a burning-plasma experiment, while also obtaining expertise from the JET collaborators on new concepts that they are initiating.
KSTAR: This collaboration provides access to the proposed KSTAR advanced tokamak physics program and also provides a venue for testing a steady-state advanced IC and LH launchers and systems. The long-pulse (300 s) operation of KSTAR presents a challenge for the design and operation of IC and LH antennas not present on shorter-pulse devices. US development and testing of the launchers and participation in the IC and LH experiments will provide information for the US program that are unavailable on any US machine.

Major new opportunities:
Improved ICRF and particle deposition capability on JET will help push the machine towards its maximum parameters and provide increased flexibility to explore AT operational scenarios. The modest efforts proposed on Tore Supra (RF, fueling) and LHD (fueling) will build on the extensive experience with long pulse operation and this experience can be applied to the proposed KSTAR efforts. KSTAR is the best opportunity for applying both long pulse and sophisticated control strategy technologies required for the AT physics program.

<u>Power and Particle Handling</u>

Description of Topic:
The successful development of high performance plasma facing components (PFCs) is central to the overall development of fusion, and has posed progressively more difficult

challenges as the power of fusion devices has increased. We must have robust PFCs in long pulse and DT devices. Helium ash must be removed and with the necessary pumping and required particle flow to the first wall region (e.g., divertor) comes intense heat. PFCs are bombarded by energetic neutrals, ions, electrons and photons and must survive intense plasma-materials interactions, such as sputtering, without contaminating the plasma. In long pulse devices, PFCs must also continuously remove high heat fluxes while withstanding off-normal heating transients. And in DT devices, remotely maintained PFCs must survive neutron radiation and simultaneous cyclic thermal heat loads while avoiding the build-up of unacceptable tritium inventories.

It is the combination of the competing requirements associated with minimizing contamination to the plasma, through the selection of armor, maximizing the heat removal, through cleverly engineered heat sinks, and joining these two features that poses our greatest challenge. The step to long pulse operation even without D/T is a major step since it requires the development of robust actively-cooled PFCs and, for superconducting devices, wall conditioning techniques that can be done in the presence of the magnetic field.

Description of Tasks:
The proposed tasks for international collaboration in power and particle handling fall into the two main areas below:

a. expertise in plasma science, plasma surface interactions and materials necessary to understand, ameliorate and exploit the interactions between the fusion plasma and the components that surround it;
b. plasma facing materials, technology and components necessary to support development of advanced fusion reactors.

Major international experimental efforts are underway to understand and control plasma surface interactions. In JET the US is helping to characterize and model the complex phenomena associated with erosion/redeposition of their carbon divertor. Plasma edge diagnostic measurements are also proposed for ASDEX-U. Wall conditioning studies are underway in TEXTOR and LHD. US plasma test facilities are being used to study the fundamental science of erosion/redeposition and tritium retention/removal with our Japanese and European colleagues.

There are also extensive international collaborations in the areas of high heat flux testing and PFC engineering. The US is testing actively cooled divertor concepts from Russia, Japan, and the European Union. Innovative manufacturing techniques such as plasma spray technology, advanced joining techniques, and new plasma-facing materials are being evaluated for JET, LHD, W7-X and KSTAR. Collaborative power deposition measurements and modeling for the Tore Supra CIEL components are also under discussion.

Benefits to Plasma Science:
The development of adequate power and particle control technology for fusion is a multi-disciplinary effort. It includes plasma science, through investigation of the plasma edge, surface science and plasma-materials interactions, and technology development in materials, joining, manufacturing, high heat flux and materials testing as well as advances in engineering such as thermalhydraulics and heat transfer. There have to be and are strong direct links between particle and power handling (PPH) technology and the Plasma Science Program. For example, in their work in wall conditioning and the characterization of particle flow, heat loads, recycling and pumping, PPH researchers participate in plasma edge experiments and provide data on impurity sources (and sinks) for plasma edge models.

PPH technologists work with the Plasma Science Program in designing, deploying and using PFCs, such as the limiters on TEXTOR and Tore Supra, and in developing designs for advanced divertor components.

Rationale for Foreign Collaboration:
Maintaining US vitality in technology for power and particle control through foreign collaborations requires US involvement in the development, deployment and use of the technology. The associated benefit to the US is that US participants incorporate this experience and expertise into the realization of future US fusion devices or define a recognized US role in the foreign fusion device. Below are some examples of the benefit to the US from international collaborations in Power and Particle handling:

a. Tore Supra: collaboration is well established; the new CIEL components will access long pulse operation; US equipment is in place for monitoring heat loads and US researchers will gain experience with and understanding of the heat loads and plasma edge behavior during long pulse operation.

b. JET: collaboration is well established; unique US expertise on erosion- redeposition, tritium retention and removal are being applied to JET; US research will advance our understanding in this critical PMI area.

c. LHD: continuing collaboration and planning provides an opportunity, through enhanced collaboration, to apply US developed technology and expertise in armor joining, high heat flux testing, high Z armor, wall conditioning and small diagnostics. US researchers will understand plasma edge conditions in stellarators and gain experience in long pulse operation and the response of PFCs that embody some US-developed technology.

d. The unique US test facilities, including PISCES (UCSD), the Plasma Materials Test Facility (Sandia) and the Tritium Plasma Experiment (Sandia/LANL), are used extensively by our international partners in collaborative experiments. In these collaborations, our international partners test their latest innovative concepts and share their results directly with the US.

Major New Opportunities:
Participation with the National Institute for Fusion Science in a future upgrade of the head for the LID (local island divertor) for the LHD Project is proposed as a significant incremental task in the table. This task enhances the existing collaboration by providing more effort in the area of armor development and testing, instrumentation on the LID head and participation in experiments with the LID. The benefit is that the US can assist the LHD Project in using technology in the areas of C and high-Z armor development and joining and high heat flux testing that have already received substantial US investment through development for ITER and other programs. These are technology advances that will have general application to PFCs for long pulse and burning plasma experiments. This enhanced involvement with the LHD Project offers the US the opportunity for first hand experience in the deployment and use of PFC technology that will be used to handle high power in long pulse experiments. An added benefit is the experience in understanding plasma edge conditions in a major high power alternate concept (stellarator) experiment. In this regard, the LID configuration is unique in that the magnetic island is believed to eliminate the "leading edge problem" encountered when modular heat sinks are used in tokamaks. The proposed technology program also links well with plasma edge studies in LHD proposed in the boundary/divertor physics portion of the Plasma Science Program.

Blankets

Description of Topic:
The demonstration of fusion as a source for energy production depends heavily on the successful development of the power extraction system surrounding the plasma. This includes the FW, blanket and shield components as the media for power extraction and replacement of tritium used in plasma burning. Solid breeders and liquid breeders have been considered with a protective solid FW. New revolutionary concepts are now being explored for high-power density (HPD) devices which can provide the capability to efficiently extract heat from the system without impairing the fundamental requirements that must be satisfied in a fusion device (e.g. tritium self-sufficiency). Examples from the APEX study are the free fall or magnetically guided liquid FW.
.
For solid breeder (SB) blankets, breeder choices are Li_2O, $LiAlO_2$, Li_4SiO_4, Li_2TiO_3, and Li_2ZrO_3 with water or helium cooling and Ferritic steel or SiC structure. Beryllium is the choice as a multiplier and the configuration is either breeder-in-tube (BIT) or breeder-out-of-tube (BOT) in a pin-type or layered-type (pebble bed). In addition to tritium self-sufficiency issue, other issues are; (1) breeder and multiplier tritium inventory, recovery and containment, (2) breeder/multiplier/structure mechanical interactions, (3) thermal control, (4) burn-up and component lifetime under irradiation, (5) purge flow, (6) structural behavior, failure modes and reliability, (7) corrosion and mass transfer, and (8) off-normal and accident conditions.

The R&D issues pertaining to liquid metal (LM) breeders are different. LM's are radiation damage-resistant and no extensive irradiation test program is required. Problems related to in-situe tritium extraction is eliminated. The key R&D issue however is the large effect of the strong magnetic field on the LM fow which consequently affect flow profiles and distribution with degraded heat transfer characteristics. Electrically insulating coating at the duct-wall surface appears to mitigate the problem and the development of such coatings is a crutial issue. Other issues are the tritium control and the purification of LM breeders. The development of permeation-reducing coating is needed, especially if the breeder is cooled with water or helium Another issue is the large electrical currents induced in the breeder in the case of plasma disruption which could lead to large forces and stresses. For free/magnetically guided liquid FW concepts proposed for HPD devices, the standing feasibility issues are the hydrodynamics and fluid mechanics of the geometrically complex free surface flow in the presence of magnetic field and/or turbulence and the effect of evaporated materials on plasma operation.

The accurate prediction of the nuclear performance and proper component/personnel protection against radiation field are fundamentals to the licensing and construction of future fusion devices. These issues can be best handled with an aggressive neutronics R&D program. Important design resonses are tritium production rate (for tritium self-sufficiency verification), nuclear heat generation (source for other thermomechanics and thermal stress analysis), induced radioactivity (for safety and scheduled maintenance purposes) and decay heat (for LOFA, LOCA accident analysis). Improving the nuclear data bases, calculational tools and modeling, and the development of specialized measuring techniques are the main objectives to narrowing any discrepancies between calculations and measurements. Available 14 MeV point (and linear) neutron source facilities are needed to perform dedicated integral experiments. Safety factors can be deduced from the observed discrepancies and conservatism can be implemented in the design of the FW/blanket/shield systems. In depth benefit/cost analysis could otherwise reveal that improving the basic data is the alternative action in narrowing these discrepancies.

Description of Tasks

The proposed tasks for international collaboration in FW/blanket/shield technology will not necessarily resolve all the issues listed above. In addition, dedicated stand-alone test facilities may be required and not necessarily part of KSTAR, JT-60U, or other devices. Partial list of grouped-issues that can be best investigated through the utilization of the existing foreign and/or national facilities are listed below:

i) MHD issues for constrained or free fall liquid metal flow:
This includes the flow profiles and pressure drop/heat transfer characteristics in constrained flow in channels with and without insulating-coating and the thermal hydraulics and fluid mechanics of free fall or magnetically-guided liquid surfaces (for turbulent or MHD laminarized/stabilized flow.) Effects of plasma disruption and the induced current/stresses under strong magnetic field is an issue that could also be a concern for plasma facing components (PFC's).

ii) Thermomechanical performance and material interaction of solid breeders with emphasis on effective interface thermal conductance and mechanical properties of packed ceramic breeder beds with multiplier and interactions in multi-layer configuration of Be, ceramic breeder, coolant, and structure. Other issue is the irradiation damage in solid breeder pebble beds at high dpa levels and impact on component lifetime under mechanical constraint.

iii) Neutronics issues including tritium self-sufficiency verification, accurate prediction of nuclear heating, induced radioactivity and decay heat, proper compenent/personnel protection against radiation field, and quantification of design margins/safety factors based on the observed discrepancies between measurements and calculations.

Proposed Tasks for FY99 and beyond:
The Group (A) issues for liquid metal blanket concepts and those innovative concepts with liquid FW can significantly be investigated using existing facilities that can be upgraded as needed. The ALEX facility at ANL can be used to study the MHD effects on flowing liquid coolants in various channel shapes and under magnetic field of varying intensity and best suited for proposed collaboration with Japan. Insulating coating can be placed for evaluation and testing with proposed collaboration with RF. The MeGA and MESO facilities at U.C.L.A. can be used for free surface liquid studies to evaluate the feasibility of innovative liquid FW/Blanket/Divertor surfaces which have the possibility to drastically improve the power handling, reliability and maintainability in HPD reactors. Collaboration with other MHD facilities in Germany, Latvia, and France is proposed. For the simulation of plasma disruption effects on LM and PFC's, there is a modest collaboration with RF in this area using plasma guns which can be extended to investigate other plasma disruption-related issues.

Previous tritium release experiments performed in the past few years [BEATRIX-II (USA/Japan/Canada), VOM (Japan), CRITIC-II (Canada), EXOTIC (EU), LIBRETO (EU)] indicated that tritium release is far less serious of a problem than previously anticipated and therefore Group (B) issues appear to be the standing ones for ceramic breeders. Many of these issues are now under investigation at the U.S. thermomechanical loop facility "UNICEX" (UNIt Cell Experiment) and HiTeC facility located at U.C.L.A. Although currently funded with a modest level, it is highly encouraged to pursue and broaden international collaboration in this area particularly if we note that FZK and JAERI have initiated studies on mechanical tests on SB under IEA collaboration. Another work proposed under IEA collaboration was discussed at a meeting held in Petten, Netherlands, September 16, 1998, pertaining to burn-up/dpa irradiation tests for solid breeder pebble bed materials using existing reactors such as JMTR (JA), ATR (US), and HFR (Netherlands).

Damage of SB under high dpa level is not currently known and international collaboration is proposed in this area.

As for Group (C) issues, there is no an operative 14 MeV point source facility at present in the U.S. that can be used to resolve these issues. Three major facilities are now operational. They are the FNS facility (JAERI, Japan), FNG (Frascati, Italy) and SNEG-13 (Near Moscow, RF). The neutron yield among these facilities varies (~5×10^{12}, n/s, ~5×10^{11} n/s, and ~3×10^{13} n/s, respectively) and can be tailored for specific neutrons tests. The first two facilities can be used for verifying the prediction capability of present codes and databases for tritium production in solid breeder (or LM) to confirm tritium self-sufficiency issue and to generate safety factors for the design purposes. Additionally, irradiation of various samples for low-activation tests and updating/verification of our current dosimetry and activation/decay heat databases can be performed at these facilities. Because of the high yield of the SNEG-13 facility, it is most suited for deep penetration tests such as verifying the adequacy of radiation protection schemes for machine components (e.g. super conducting magnet) and personnel from transported and/or streamed neutrons and gamma rays. It can also be used to quantify the peaking factors used in shielding design to account for streaming through openings and gaps between blanket segments.

FY99 funded Tasks:
In addition to the FY99 funded task on the simulation of plasma disruption effects, two other tasks will be in progress during FY99 and are under IEA-Co-operative Program on Nuclear Technology of Fusion Reactors. The Test Blanket Working Group (TBWG) meets annually to review work performed by the U.S., JA, EU, and RF in designing relevant integrated test modules to be placed in dedicated test ports in future test facilities like ITER. The U.S. adopted Li2TiO3/Ferritic Steel and Li/V blanket modules for the text DEMO reactors. Integrated tests (thermal hydraulics, thermomechanics, lifetime evaluation, etc.) are planned by each party under realistic conditions (e.g. fluence). The other international collaboration is under the same IEA Program, sub-task “neutronics”, where several neutronics issues are investigated independently by JA, EU, RF, and the U.S. Focus is placed on performing integral experiments on other breeders (Li2ZrO3, Li4SiO4), low-activation materials and code development. It is currently receiving very modest funding for FY99 and it is worth maintaining this activity in future at reasonable funding.

Benefits to Fusion Science:
Advancing the technology of power extraction and breeding in the FW/Blanket/Shield system will have benefits to several engineering disciplines, in particular, and to fusion science, in general. For example, in magnetically controlled fusion devices, advances in properly mitigating the MHD effects on LM pressure drop and heat removal capability could ultimately maintain high magnetic field for plasma control and yet power can be efficiently extracted from the blanket. Modeling and understanding the effects of liquid evaporation on plasma performance in free surface liquid FW concepts and the impact of plasma disruption on PFC’s is an example of strong link between plasma science and blanket engineering. Extending the lifetime and operation limits of solid breeders under simulating irradiation conditions from the plasma and yet maintaining adequate tritium breeding and extraction could lead to maturing the fusion science application for advanced energy extraction systems. In addition, improving nuclear physics database for 14 MeV neutrons interactions by providing accurate data on neutron cross sections for transport, scattering, breeding, activation, and multiplication is a valuable benefit to fusion science that can be achieved from performing neutronics experiments with the existing 14 MeV neutron sources.

Rationale for Foreign Collaboration:

The involvement of the U.S. in international collaboration with researchers abroad who have the expertise and strong background in blanket technology will produce an international forum through which latest knowledge and advances in the field could be accessed by the U.S. This benefit to the U.S. could be even magnified if a unique foreign facility is used for that purpose with the obvious advantage of saving on the construction and operational cost. Examples are the FNS and SNEG-13 facilities located in Japan and Moscow area, respectively, for neutronics tests and the JMTR and the HFR facilities located in Japan and Netherlands, respectively, for irradiation tests on solid breeders. On the other hands, incoming participation of foreign scientists and researchers in experiments on U.S. facilities such as ALEX, MeGA, ATR, UNICEX, and HiTeC will open doors for new ideas, approaches and solutions for technical issues pertaining to blanket technology.

Magnetics Technology

Description of Topic:
The long-range goal of the magnet technology program is to provide both low- and high-temperature superconducting materials and technology expertise necessary to develop and evolve proof of principle experiments for alternate concepts; design, construct and upgrade present and proposed tokamak experiments; and provide innovative magnetic components and devices for basic studies in plasma science.

Description of Tasks:
The main international collaboration is the testing of the CS Model Coil at the JAERI Magnet Test Facility in Naka, Japan. This test will provide the test data that will validate US design codes, demonstrate the performance of a full-size reactor relevant coil, and it will provide a database that can be used for reduced cost design of future superconducting magnets. Other proposed international collaborations include work with KSTAR on a helium isolator to increase voltage standoff, development of fiber optics quench sensors, and toroidal field joint tests at MIT's Pulse Test Facility (PTF). A collaboration is also proposed with Culham (UKAEA) on feltmetal joints and magnet design for MAST.

Benefits to Plasma Science:
The development of high-performance, reduced-cost superconducting magnets is of fundamental importance for any next-step device. The Magnetics Technology community works in close collaboration with both the tokamak and alternate concept plasma physics communities to understand their needs and to contribute to the design of required superconducting materials, components and magnets and magnet systems. For example, Tokamak and Stellarator power point designs have used peak magnetic fields in the 13-16 Tesla range. Optimization without conductor constraints leads to 20 Tesla peak fields. Magnet structures will always be costly to disassemble, requiring a goal of full life expectancy without replacement. Concepts which favor reliable operation have been a design driver in ITER and the Model Coils. The magnet systems are likely to always be a significant component of capital cost. There are opportunities for significant cost reduction relative to the current ITER design point and for any new device

Rationale for Foreign Collaboration:
In addition to collaborative programs involving applications of the technologies on foreign confinement devices, the Magnetics Technology program is involved at all levels in joint R&D that supports the generic development program objectives as well as the ITER project. Strategic partnerships with international development activities are used to supplement areas which cannot be adequately addressed given the limited US funding. These activities generally involve the use of test stands and other facilities within the US and abroad and

effectively capitalize on the extensive US investment in its own development facilities. A good example in Magnetics Technology is the testing of the CS model coil (MIT/JAERI) at the JAERI test stand. Other international collaborations make effective use of magnet test facilities such as the Pulse Test Facility (PTF) at MIT, TOSKA in Germany and SULTAN in Switzerland.

Major New Opportunities:
High-Temperature Superconductors are a major new opportunity in Magnetics Technology. They offer the potential to reduce refrigeration, simplify cryostats, and bore tubes. They also have potential for very high field magnets, magnet insert coils, and highly efficient current leads. There is a need for improvements in Jc, cost, piece length, and mechanical strength. International collaboration can play an important role in developing this new technology.

<u>Operations Processes (Tritium, Safety, Remote Handling)</u>

Description of Topic:

This topic encompasses technologies and processes normally associated with operational issues such as tritium systems and tritium processing, safety aspects of magnetic confinement devices and remote handling and associated diagnostic techniques. These issues are particularly relevant to next step devices, near term burning plasma experiments, large proof of performance devices (JET, JT-60, LHD) and joint international development efforts involving large scale facilities such as the Tritium Systems Test Assembly (TSTA). They are important enabling technologies in support of the fusion program's strategic objective to pursue the energy option internationally.

The respective long range goals of these technology program elements are 1) demonstrate technologies for the safe and efficient handling of tritium, 2) develop a thorough understanding of enabling technology related safety issues (divertor, tritium, and magnets) to assess the overall impact on fusion safety and 3) demonstrate remote handling technology in the areas of in-vessel inspection and welding/cutting.

Description of Tasks:

The proposed tasks for international collaboration in this area are summarized below:

1) continuation existing US/Japan collaboration (Annex IV JAERI/US Collaboration) involving the technology for fusion-fuel processing and D&D activities at TSTA and TFTR, 2) proposed collaborations in the areas of analysis of JET dust for tritium mobility studies, improvement of the efficiency of JET's impurity processing system and cryogenic distillation system by implementing US developed techniques and hardware, and
3) implementation of non intrusive diagnostics (laser radar) to measure PFC motion during disruptions and monitor

Benefit:

The technologies associated with this collaboration area will be needed for the US program to fully exploit its strategy to pursue the fusion energy option on an international scale. Collaboration provides the US with access to advanced physical plants (JET Advanced Gas Handling System, LHD, JT-60, Tritium Processing Laboratory at JAERI) that are not available in the US program and unique test conditions to test US developed hardware and techniques (CLR, Palladium Membrane Reactor etc.). Continued collaboration with Japan in the area of tritium systems development and D&D activities provides and important additional source of funding and incoming facilities to augment TSTA and PPPL activities in these areas. Finally hardware contributions and exchange of expertise in these and other enabling technology areas have been beneficial in establishing science program links to these facilities.

Rationale for Foreign Collaboration:

Maintaining US involvement in this through foreign collaborations ensures that the US will maintain critical expertise in reactor relevant technologies needed for any future burning plasma/ignition device. The proposed new collaborations target large scale proof of performance devices that will face issues relevant to safe and efficient use of tritium and associated safety issues (such as tritium mobilization and in vessel tritium inventory control), disruption mediation, and remote viewing/mapping of plasma facing components.

Major New Opportunities:

JET

Collection and analysis of JET dust. The accidental release of tritium retained in dust is a potential hazard in burning plasma devices. The US will benefit from this activity by gaining access to facility/test conditions (high T concentrations) unavailable in the US program.

JET/JT-60

Measure nonintrusively PFC motion (i.e., the CLR viewing the object through a window) during disruptions using the coherent FM laser radar and utilize and benchmark codes that predict the motion. The ability of the CLR to obtain Doppler corrected range data would be utilized to measure the amplitude and frequency of the PFC motion. The US will benefit from this activity by gaining access to facilities to test this unique capability that will lead to a better understanding of disruptions and their effects by correlating the results with the plasma parameters and the forces acting on PFCs.